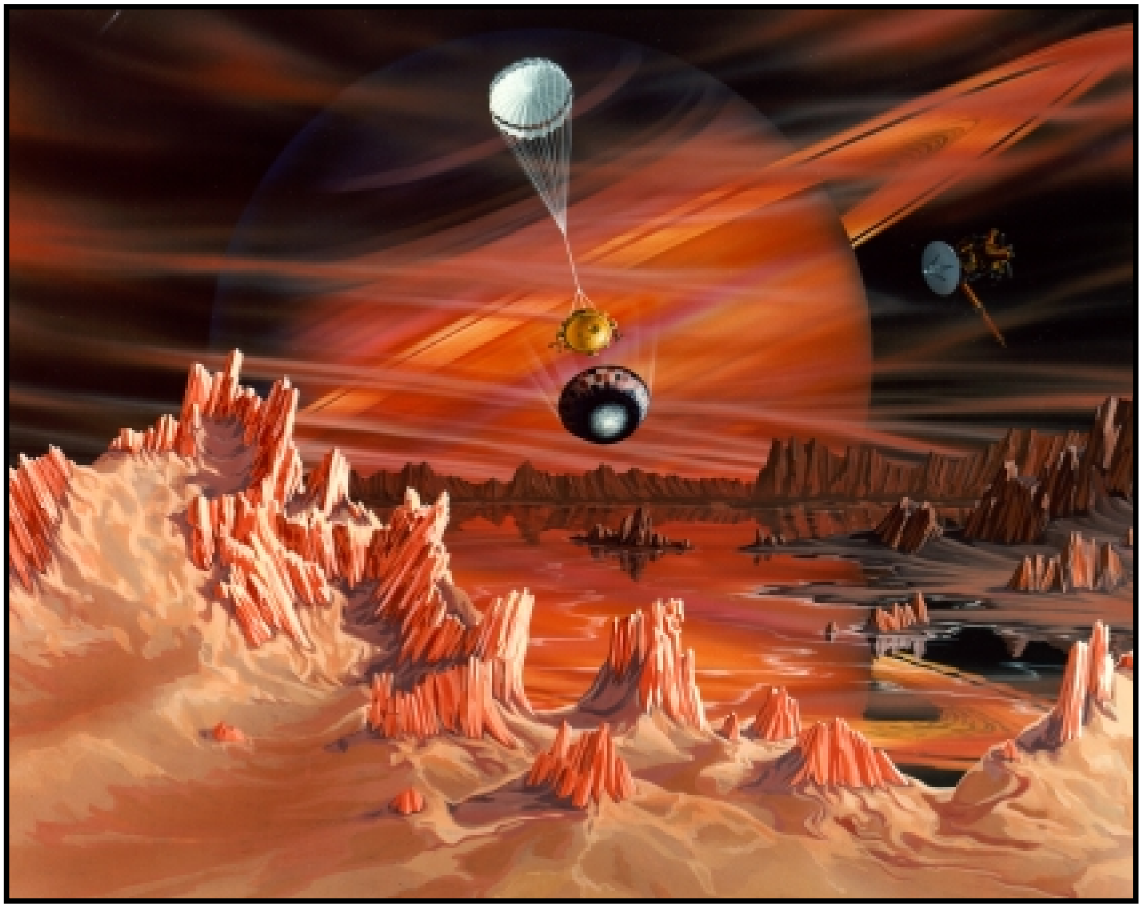

Artist conception of Huygens Saturn Probe Titan Delivered by Cassini.
Credit: Craig Attebery, courtesy JPL

Planetary Systems Branch (SST) Overview

The overall research effort in the Planetary Systems Branch is directed at acquiring new, fundamental knowledge about the origins of stars and planetary systems and life itself. These studies are an integral part of NASA's overarching thrust in Astrobiology. Principal research programs include studies of the formation of stars and planets and the early history of the solar system, studies of planetary atmospheres and climate, investigation of the dynamics of planetary disks and rings, work on problems associated with the Martian surface including resource utilization and environments for the origin of life, and other programs (chiefly theoretical) involving stellar and planetary dynamics, radiative processes in stars and the interstellar medium, and investigation of the physical and chemical conditions in molecular clouds and star formation regions. Recent research involves development of informatics techniques to extract scientific information from modern large datasets. Scientists in the branch also support NASA flight missions through participation on various mission science teams. The primary product of the Branch is new knowledge about the nature of the universe, presented and published in the open literature.

Bruce F. Smith

Chief, Planetary Systems Branch (SST)

ORGANIC CHEMISTRY LEADING TO LIFE

Emma Bakes, Alexander Tielens, Charles Bauschlicher, Christopher P. McKay, Stephen Walch, William Borucki, Robert Whitten, Bishun Khare, Louis Allamandola, Douglas Hudgins, Sebastien Lebonnois and Hiroshi Imanaka

Work has been done by Principal Investigator Bakes and collaborators on three primary research topics.

1. The Formation of the Building Blocks of Life in Space
   Emma Bakes, Stephen Walch and Charles Bauschlicher

Our Solar System was formed from the primordial ISM when it collapsed to form a disk of gas and dust grains. Everything that comprises the solid material in our planetary system originates from primordial interstellar dust. There is increasing evidence that primordial interstellar material is intimately related to cometary and meteoritic matter in our Solar System. Amino acids are termed "prebiotic" because they precede the formation of all biological life. Historically, amino acids were thought to reside on our planet only. Recently, however, they have been discovered not only in solid chunks of meteoritic rock from the outer Solar System, but in the material between the stars (the "interstellar medium" or ISM). This has profound and far reaching implications for the origins of life. If the molecules which precede life exist between the stars, then life is a potentially universal phenomenon.

The primary goals of the proposed research were to 1) predict the chemical pathways and energetics for amino acid synthesis under astrophysically relevant conditions, 2) provide evidence of the survivability of amino acids in the hostile environment of interstellar space 3) predict infrared spectra for of the relevantspecies and 4) insert the results of (1), (2) and (3) into an astrochemical model to interpret and analyze astrophysical infrared data from the chemically richest region of our Galaxy, Sagittarius B2, where a possible detection of glycine, the simplest amino acid, was made. This work has shown that it is possible to make amino acids in interstellar space on solid interstellar dust grains (but not in the gas). The amino acids on these dust grains may then become part of a new solar system when the solid grains collapse to form planets and rocky bodies in the planetary system. In short, it is possible that some of the amino acids found on Earth today originated in the harsh and cold reaches of interstellar space.

2. The Formation of Macromolecules and Precursors to Biology in the Titan Haze
   Emma Bakes, Charles Bauschlicher, C.P. McKay, William Borucki, Robert Whitten, Bishun Khare, Sebastien Lebonnois and Hiroshi Imanaka

This research has begun to bridge the gap existing in current models of Titan chemistry. It has established that it is possible to form both neutral and cationic, pure and nitrogenated macromolecules containing up to 10 carbon atoms so far. Larger molecules are on the way to being analysed using quantum chemical techniques. This knowledge represents an enormous breakthrough, advocating the ease and energetically favorable formation of macromolecules which can then play a key part in Titan's thermodynamics, chemistry and aerosol formation. 2) Experiment have been initiated in the laboratory to investigate the chemical scheme detailed in (1) to investigate how the starting mixture, temperature, pressure and molecular complexity alter the final products. Results so far back up quantum chemical breakthroughs made in (1). 3) The formation of molecular hydrogen via aerosol surface catalysis has been investigated and found to play a significant role in the formationand subsequent escape of this molecule from Titan's atmosphere, solving a longstanding problem in the Titan haze composition. 4) The charging and agglomeration of Titan haze aerosols has been investigated and it can account for daily and (potentially) seasonal variations in the haze albedo. This occurs via the agglomeration of anionic PAHs and highly positively charged aerosols during the daytime or summer phases of Titan. It is erroneous to consider a monodisperse aerosol population with one charge - the situation is much more complex and dramatically changes our view of Titan's atmosphere. This is very controversial and will likely cause a storm in the field. 5) The above discoveries may radically change Titan haze conductivity and a new model is currently being formed of the charging of the Titan haze aerosols. This will help revise the results intended to guide the Cassini Huygens probe, which drops into the Titan haze in 2004.

3. Solving the Thirty Year Old Problem of the Unidentified Interstellar Infrared Emission Features
Emma Bakes, Alexander Tielens, Charles Bauschlicher, Louis Allamandola and Douglas Hudgins

Strong infrared emission features between 3.3 and 12.7 microns are ubiquitous and are the most luminous mid-IR spectral features originating from the ambient interstellar medium (ISM). They are valuable diagnostics of its chemical composition, thermal excitation and evolution. These features are observed in many astronomical sources at various stages of evolution, including reflection nebulae, HII regions, young stellar objects, photodissociation regions, post asymptotic giant branch stars, planetary nebulae, transition objects, novae, the Galactic disk and even extragalactic sources. These mysterious features are generally attributed to polycyclic aromatic hydrocarbon (PAH) molecules, although exact identification of the carriers of these IR features with specific molecules has remained elusive, leading to their being termed the "unidentified infrared (UIR) emission features". This research has made substantial inroads into clarifying the nature of the carriers of the "UIR" emission. A state of the art model of interstellar IR emission and macromolecular chemistry was constructed. The inclusion of quantum chemistry has taken the prediction of IR emission and the chemical evolution of PAHs to a superior level of theory surpassing former studies. It has also enabled a logical and systematic search for the "UIR" emission carriers in a variety of star forming regions, guided by the fundamental laws of quantum physics. The answer to one of the key questions in astrophysics, "What is the nature of the carriers of the UIR emission features?" is within our grasp. We are on the verge of a breakthrough in solving this 30 year old problem. ❑

PROBING DUST PROCESSING EVENTS IN ACCRETION DISK ATMOSPHERES USING TWO-DIMENSIONAL RADIATIVE TRANSFER MODELS

K. Robbins Bell, Diane Wooden, David Harker, and Charles Woodward

Progress has been made in observing and modeling temporally variable dust emission features in young stars surrounded by protoplanetary accretion disks. Multi-epoch mid-infrared spectrophotometry of pre-main sequence (PMS) stars, including low mass PMS T Tauri stars and intermediate mass PMS Herbig Ae / Be stars, with the Ames Hi-efficiency Faint Object Grating Spectrometer (HIFOGS) over the 7.5 – 13.5 micron wavelength range has confirmed the measurement of variable dust emission features. The HIFOGS spectrophotometric observations reveal changes in strength in either the 9.7 micron amorphous silicate resonance or the 8.6 micron and / or 11.25 micron polycyclic aromatic hydrocarbon (PAH) bands in a half dozen PMS stars. While the dust emission features change on timescales of months to years, the underlying infrared continua remain constant in flux density. The interpretation of this variability is that dust in the tenuous regions above the optically disks is being chemically altered through exposure to stellar radiation. These processing events appear to be occurring at disk radii comparable to or larger than the Earth's orbit of 1 astronomical unit (AU) and may provide clues to the dynamics of the active planet-forming region below the disk photosphere.

Two-dimensional radiative transfer models have been developed and are being used to model these time variable spectra. These new models allow synthesis of spectral energy distributions of complex disk geometries that include inner gaps and disk swelling due to local opacity effects such as expected from vertical structure models. The 2-d radiative transfer models are being used to interpret data from broad wavelength spectral energy distributions derived from ground-based photometry and HIFOGS time variable spectroscopy as well as from the Infrared Space Observatory (ISO) Short Wavelength Spectrometer (SWS) 6 – 45 micron spectra. ❑

THE KEPLER MISSION: A PHOTOMETRIC MISSION TO DETERMINE THE FREQUENCY OF EARTH-SIZE PLANETS IN THE HABITABILITY ZONE OF SOLAR-LIKE STARS

William Borucki and David Koch

Kepler is a Discovery-class space mission designed to detect and characterize Earth-size planets around solar-like stars. The sizes of the planets are determined from the decrease in light from a star that occurs during planetary transits and the orbital period is determined from the repeatability of the transits. The orbital radius and the nearness of the planet to the habitability zone is estimated from ancillary measurements of the stellar mass and brightness. Such measurements determine the spacing of planets, their distribution of size with orbital distance, and their variation with stellar type and multiplicity. Because thousands of stars must be continually monitored to detect the transits, extensive information on the stars can be obtained on their rotation rates and activity cycles. Observations of p-mode oscillations also provides information on age and metallicity of the parent stars.

These goals are accomplished by continuously and simultaneously monitoring a single field of 100,000 solar-like stars for evidence of brightness changes caused by transits of Earth-size or larger planets. To obtain the high precision needed to find planets as small as the Earth and Venus, a wide field of view, 0.95m aperture Schmidt telescope with an array of CCD detectors at its focal plane must be located outside the Earth's atmosphere. Both SMM (Solar Maximum Mission) and SOHO observations of the low-level variability of the Sun (~1:100,000) on the time scales of a transit (4 to 16 hours), and our laboratory measurements of the photometric precision of charge-coupled devices (1:100,000) show that the detection of planets as small as the Earth is practical. If most solar-like stars have terrestrial-size planets in their habitable zone, then several hundred planetary systems should be detected. Many additional planets should be detected with shorter orbital periods. Planets as small as Mars or even Mercury could be found if they have orbital periods of a week or less. Based on the Doppler velocity data obtained by Marcy and Butler, approximately 1000 giant inner planets should be discovered from their reflected light.

The Kepler Mission was selected on 21 December 2001 for a launch opportunity and is expected to be launched into a heliocentric orbit in 2007. A four year mission is planned with the capability of operating for an additional two years. The additional two years would nearly double the number of detections of planets in the habitable zone of G-dwarf stars like our Sun.

The spacecraft and instrument will be build by Ball Aerospace Technology Corp. (BATC) of Boulder, CO. BATC has built most of the optical instruments used in the Hubble Space Telescope and is the industrial partner for the Deep Impact Discovery Mission. The Space Telescope Science Institute (STScI) is a partner on the Kepler Mission. Ron Gilliland is in charge of calibrating and archiving the data as well as using acoustic mode data to determine the age and composition of the brighter stars. His method of frame subtraction will be used to remove the effects of dim background stars.

Dave Latham and his colleagues at the Smithsonian Astrophysical Observatory will perform ground-based spectroscopy on the 225,000 stars in the Cygnus star field that Kepler will view. These data will be used to select the target stars by culling out evolved stars that are too large to show planetary transits. They will also examine candidate planets to remove false positives caused by the presence of white dwarf companions.

Alan Gould from the Lawrence Hall of Science and Edna DeVore from the SETI Institute are leading the education and outreach programs to bring the Kepler discoveries into class rooms and to the attention of the general public. ❏

EFFECT OF NEGATIVE IONS ON THE CONDUCTIVITY OF TITAN'S LOWER ATMOSPHERE

William J. Borucki, Emma L. Bakes, and Robert C. Whitten

In a paper published in 1984, Borucki and colleagues calculated the electrical conductivity and electrical charge on aerosols in Titan's atmosphere due to the ionization by galactic cosmic rays and electron precipitation from Saturn's magnetosphere. Based on these calculations, an experiment was designed to fly on entry probe of the Cassini Mission to measure Titan's conductivity. The calculations showed that the lower atmosphere must be substantially more conducting than the atmospheres of Earth and Venus because of the high concentration of free electrons. The prediction of a high conductivity is based on the lack of electrophillic species which could form negative ions with low mobility and thereby reduce the number of free electrons. At that time, no molecular species capable of forming negative ions in concentrations sufficient to perturb the atmospheric conductivity were identified. Recently, E. Bakes and her colleagues have been investigating the formation of polycyclic aromatic hydrocarbons (PAH) using quantum mechanical methods. Their calculations indicate that these molecules will be highly electrophillic and are likely to be present in the atmosphere at mixing ratios of order one part per ten million. Revision of the atmospheric model is underway to account for the presence of the negative ions formed from the PAHs and to predict their effect on Titan's atmospheric conductivity. ❑

THE VULCAN PHOTOMETER: A DEDICATED PHOTOMETER FOR EXTRASOLAR PLANET SEARCHES

William Borucki, Douglas Caldwell, David G. Koch, and Jon Jenkins

A small dedicated photometer to detect extrasolar planets has been constructed and tested at Mt. Hamilton, California. It simultaneously monitors 3000 stars brighter than 12th magnitude within each star field in the galactic plane. Observations are conducted all night every clear night of the year. A single field is monitored at a cadence of eight images per hour for a period of about three months. When the data are folded and phased to discover low amplitude transits, the relative precision of one-hour samples is about 1 part per thousand. This precision is sufficient to find jovian-size planets orbiting solar-like stars, which have signal amplitudes from 5 to 50 parts per thousand depending on the sizes of the planet and star.

Nearly one hundred variable stars are found in each star field in each of the two star fields observed. About fifty of these are eclipsing binary stars, some with amplitudes of only a few percent. Three of these showed transits signatures like those expected from planetary companions. These stars were then observed with high-precision spectroscopy at other observatories to determine the mass of the secondary object. The spectra indicate that two candidates are nearly identical stars in binary pairs in grazing orbits. Spectroscopic observations showed the third object to be a high mass-ratio single-lined binary with a stellar companion similar in size to a jovian-size planet. Detection of the extrasolar planet orbiting the star HD209458 produced an easily recognized signal proving that the photometer has the necessary relative precision to find planetary companions. ❑

EXTRASOLAR PLANET DETECTOR FOR THE SOUTH POLE

Douglas A. Caldwell, Robert L. Showen, Kevin R. Martin, William J. Borucki, and Zoran Ninkov

Recent discoveries of a wide variety of planetary systems highlight the need for statistical information on the numbers and properties of extrasolar planets in order to understand planetary formation and evolution. Transit photometry (observing a planet pass in front of its star) can reveal a wealth of information for ~10% of those planets with orbital periods of one week or less. Observations of the transit of the extrasolar planet HD 209458b have resulted in the first unambiguous determination of mass and density, as well as the first detection of the atmosphere of an extrasolar planet. The goal of this work is to extend the transit photometry being done at Ames by developing a photometer for use at the South Pole.

Reliable detection of a transiting extrasolar planet requires observations of at least three transits in order to confirm the periodic nature of the signal. Therefore, the detection rate depends strongly on the duration and phase coverage of the observations. In the ideal case of continuous observation three transits could be seen in three times the longest period to be detected (~7 days). The closest one can get to continuous observation on Earth is the long winter night at the poles. The South Pole is more practical because of its permanent station, favorable weather, and excellent astronomical conditions. The three-transit detection rate at the South Pole is three times better than that of a mid-latitude site, even with time lost due to bad weather - historically estimated at 50%. In one month of observation the detection-rate is equivalent to that from three months of mid-latitude observation. The Poles have the added advantage of constant elevations for the stars being monitored, thereby eliminating the large nightly flux changes as the stars rise and set.

A prototype photometer for use at the South Pole has been constructed and tested at Ames Research Center. It is based on the Ames Vulcan photometer, which has been in operation at Lick Observatory for several years. The prototype, ‘Vulcan-South,’ was designed with the goal of understanding the operating environment at the South Pole. In particular, the system must be able to operate largely unattended in the extreme cold and blowing snow. The prototype was designed to be as close as possible to a fully-capable transit detection system, including a science-grade charge coupled device (CCD) camera, full-motion mount, and wide field-of-view optics. The mount and camera-frame were designed to work at –45º Celsius (the late-summer temperature at the Pole), using low-thermal-expansion material and dry lubrication. A heating and insulation system was designed to keep the CCD and mount electronics within operating specifications as well as to protect moving parts from blowing ice crystals. The photometer was instrumented to monitor temperatures throughout. Subsystems were tested in a cold-chamber during the design and construction phase.

The Vulcan-South photometer was deployed to Antarctica in the austral summer of 2001. The system was installed on the roof of the astronomy building approximately 1 kilometer from the geographic South Pole and operated for five days. The heating and insulation system worked as designed, keeping the CCD camera, optical, and mechanical systems between –5 and –15 Celsius, with ambient near –35 Celsius. Based on the results of deployment, and using automation developed for the Vulcan project, the design of a winter-over photometer for the South Pole has been completed. ❑

CIRCUMSTELLAR CARBONACEOUS DUST

Jean E. Chiar and Alexander G.G.M. Tielens

Aromatic (chain-like) hydrocarbon material is present in both circumstellar and interstellar environments. Its presence is evidenced by either emission or absorption features, depending on the excitation conditions, at wavelengths corresponding to the fundamental vibrational frequencies of carbon-carbon and carbon-hydrogen bonds. An infrared absorption feature has been detected at 6.2 microns towards several objects that sample large path lengths of diffuse interstellar medium dust. It was originally proposed that the aromatic materials were thus residing in the diffuse interstellar medium, and were not related to the objects themselves.

However, our study shows that the 6.2 micron absorption feature is actually circumstellar in nature and is produced by the WC-type Wolf Rayet stars being used to probe the diffuse interstellar medium along their line of sight. These results have implications for dust nucleation in the hostile environment around these hot stars, a topic that has only recently been theoretically explored. Since the circumstellar visual extinction toward these objects is minimal (around 1 magnitude), these dust grains have to be rather large (around 1 micron) and point toward dense clumps as the sites of dust formation.

Late-type WC stars, massive hot stars with fast dense stellar winds, are undergoing extensive mass loss and show the products of helium burning at the surface. Since their circumstellar material is carbon-rich and hydrogen poor, we attribute the absorption feature at 6.2 microns in their spectra to circumstellar amorphous carbon dust.

The 6.2 micron absorption feature is also detected toward the enigmatic cocoon stars in the Galactic Center Quintuplet Cluster. Thus, as a corollary, our results support a previous suggestion that these sources are themselves late-type WC stars. This absorption feature is not detected in the diffuse interstellar medium toward lines of sight which sample only interstellar dust, with no possible contribution from the circumstellar dust of dusty late-type WC Wolf-Rayet stars. ❑

ORGANICS AND ICES TOWARD THE GALACTIC CENTER

Jean E. Chiar, Andrew J. Adamson, Yvonne J. Pendleton, and Douglas C.B. Whittet

High-quality, spatially resolved spectra were obtained with the mid-infrared spectrometer CGS4, on the United Kingdom Infrared Telescope, in order to disentangle absorption components due to dense cloud material and diffuse interstellar medium dust along the line of sight toward the Galactic Center. We find that both absorption components vary significantly across the small 2-parsec field studied implying small-scale inhomogeneity in both the (foreground) diffuse interstellar medium and the dense molecular clouds. Figure 10 shows that our data are uniquely suited to defining the profiles of the dense cloud water-ice feature and the diffuse interstellar medium 3.4 micron aliphatic (chain-like) hydrocarbon feature, compared with previous studies which relied on fitting local continua over a small wavelength range. A new diffuse ISM absorption feature at 3.3 microns is revealed. The central wavelength is indicative of polycyclic aromatic hydrocarbons (PAHs), however its width is broader than the well-studied PAH emission features and the absorption feature seen toward the Galactic Center Quintuplet sources to the north. The difference in profile could be due to differences in temperature and/or carrier(s) present in these regions. ❑

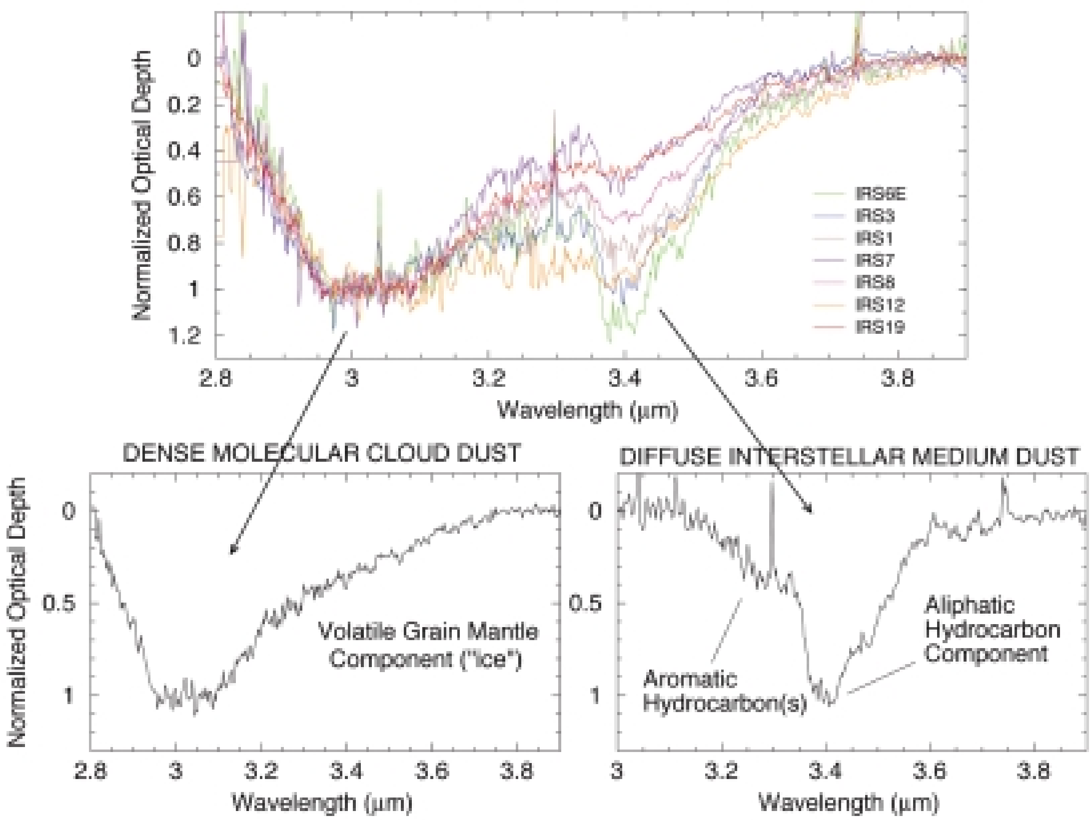

Figure 10: The spectroscopic signatures of key ice and organic dust components along the Galactic Center line of sight. Ice and hydrocarbon absorption vary independently of each other.

ARTIFICIAL INTELLIGENCE TECHNIQUES FOR LARGE-SCALE SURVEYS OF SPACE SCIENCE DATA

Paul R Gazis, Aaron Barnes, and Clark Glymour

Many problems in space physics require large-scale surveys of extensive data sets to identify and classify qualitative features such as shocks, discontinuities, energetic particle enhancements, or specific types of spectra. Such surveys can be difficult to accomplish using conventional programming techniques and the manpower requirements associated with direct physical examination of the relevant data sets can be prohibitive. Artificial intelligence (AI) techniques provide a potential solution to many of the problems associated with large-scale surveys. This is a mature technology for which the relevant techniques are well-documented and understood, but as yet, the space science community has made little use of AI techniques.

Investigators at the Ames Space Science Division, in collaboration with Carnegie Mellon University, have been examining a broad range of different AI techniques to evaluate their effectiveness for large-scale surveys of space science data. These techniques include traditional Expert Systems, statistical methods, and different neural network-based approaches. Unsupervised classification using self-organizing maps (SOMs) has proved particularly productive. A suite of tools have been developed, tested, and applied to a wide range of problems that involve one-dimensional pattern recognition, such as the classification of visual and infra-red spectra and the identification of events in time series of stellar occultation or solar wind plasma and interplanetary magnetic field (IMF) data. These tools have already produced valuable results in surveys of interplanetary shocks observed by the Voyager 1 and 2 and Pioneer 10 and 11 spacecraft. These tools should be immediately useful for many problems involving large-scale surveys of extended data sets that would be difficult or impossible to perform using any other means. ❑

ORIGIN OF THE THERMAL INERTIA CONTINENTS ON MARS

Robert M. Haberle

The surface of Mars can be classified into two major “continents” which are distinguished by the ability of their surface material to respond to solar heating. Low thermal inertia continents respond rapidly to solar heating and experience significant daily variations in surface temperature. High thermal inertia continents do not respond rapidly to solar heating and experience much more subdued temperature swings. These different behaviors are due to the nature of the surface materials comprising these continents. The low thermal inertia continents contain fine sandy materials (poor thermal conductors) while the high thermal inertia regions consist of hard consolidated rocky materials (good thermal conductors). These continents have fairly well defined boundaries and occupy vast regions of the planet. The question is how did they come about?

The answer appears to be related to the planets global scale wind systems, which in turn are strongly controlled by topography. The low thermal inertia continents represent accumulations of fine particles, which settle out of the atmosphere. In these regions, winds are relatively calm and once the dust settles to the surface it tends to stay there. On the other hand, the high thermal inertia regions experience strong winds, which scour the surface clean and expose the underlying bedrock.

This hypothesis was tested with the Ames Research Center Mars General Circulation Model (GCM). The GCM predicts Martian wind systems using state-of-the-art numerical methods. These winds were then used to estimate how much dust could be lifted annually from the surface, a quantity called the “deflation potential”. The spatial distribution of the deflation potential was examined for a variety of orbital configurations since Mars’ orbit properties are known to oscillate considerably on time scales ranging from tens of thousands of years to millions of years. In particular, the planets obliquity (the angle between its spin axis and orbit plane) may have varied anywhere from almost 0° to as high as 60° during the past 20 or 30 million years or so. Such changes were found to have a profound effect on the planets climate system. Yet, surprisingly, the regions of low thermal inertia never experienced significant deflation events regardless of the planets orbital configuration. Figure 11 shows a typical spatial pattern of the deflation potential as simulated by the GCM. Also shown is the present day distribution of thermal inertial. The correlation is remarkable.

If surface winds never get strong enough to erode away the fine material in the low thermal inertia regions, then it implies that these “continents” are old, much older than previously thought. In fact, these accumulations must have begun very early in the planet’s history - 3.5 billion years ago - when its topography stabilized to near its present elevation. This notion can be easily tested with future landers and / or sample return missions. If correct, it means there is a readily accessible climate record that dates all the back to very early in the planet’s history. ❑

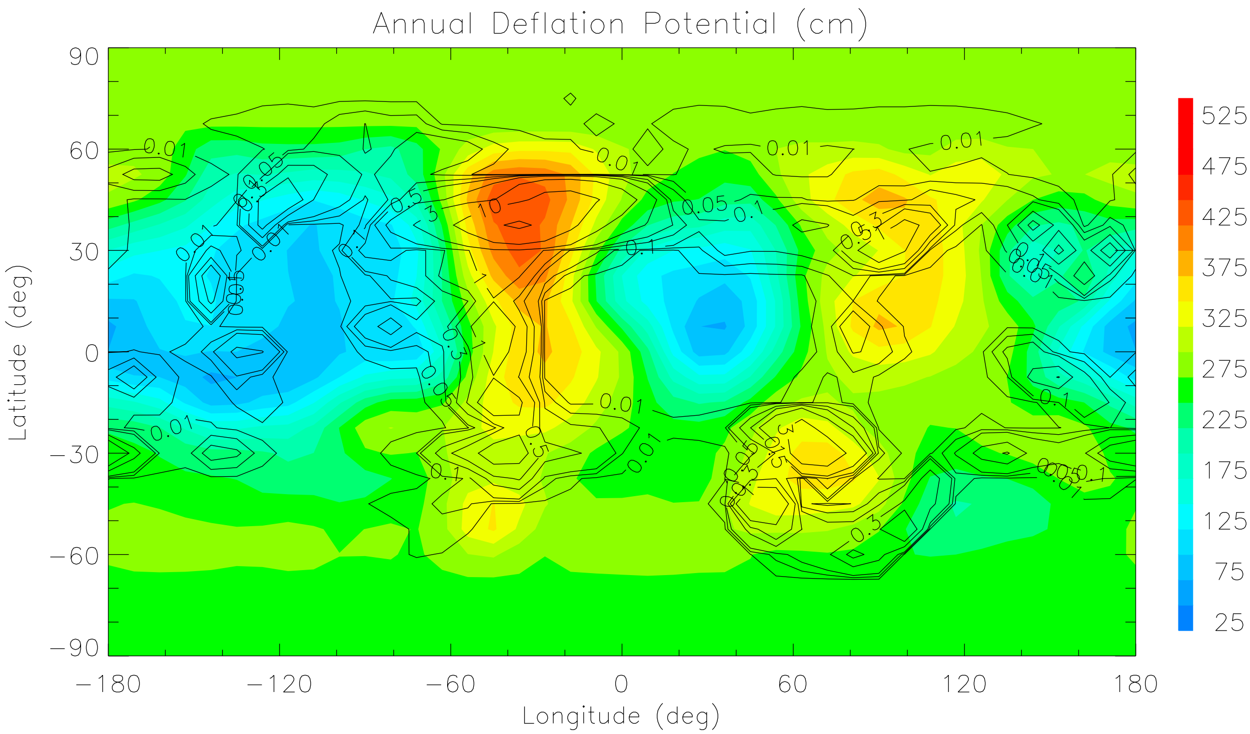

Figure 11: Color shading indicates thermal inertia in SI units. Scale bar is on the right. Black contours represent GCM prediction of the deflation potential in cm. Note the high positive correlation between the deflation potential and thermal inertia.

THE CENTER FOR STAR FORMATION STUDIES

D. Hollenbach and K. Robbins Bell

The Center for Star Formation Studies, a consortium of scientists from the Space Science Division at Ames and the Astronomy Departments of the University of California at Berkeley and Santa Cruz, conducts a coordinated program of theoretical research on star and planet formation. The Center, under the directorship of D. Hollenbach (NASA Ames), supports postdoctoral fellows, senior visitors, and students, meets regularly at Ames to exchange ideas and to present informal seminars on current research, hosts visits of outside scientists, and conducts a week-long workshop on selected aspects of star and planet formation each summer.

In July 2001 the Center held an international workshop entitled “Star Formation in the Galactic Context” on the University of California / Santa Cruz campus. The weeklong workshop had approximately 130 attendees, and included an invited talk by D. Hollenbach on “Neutral Phases of the Interstellar Medium: Is Star Formation Self Regulated by the Ultraviolet Field in a Galaxy?”.

One focus of the NASA Ames portion of the research work in the Center in 2001 involved the study of the thermal balance, chemistry, dynamics, and spectra of disks of gas and dust orbiting young stars. These disks, called “protoplanetary disks”, are the birthplaces of planets, and originally consist primarily of molecular hydrogen gas, with small amounts of other gaseous species such as carbon monoxide and a small admixture of dust particles. A number of processes heat the gas and dust in these disks, including radiation from the central star, radiation from a nearby luminous star, and the gravitational energy released as the gas and dust spirals toward the star. Previous researchers have focuses on the heating of the dust and the infrared spectrum of the dust; Ames researchers focused on the gas and the infrared and millimeter wavelength emission from the gas. Comparison of data from NASA missions (see below) with these models provides constraints on the distribution of gas and dust and the likelihood and duration of planet formation. In addition, the heating in the outer regions of the disks can be sufficient to drive evaporation of the outer disk regions in times short compared to the times required for planet formation, and thus thwart or modify planet formation in the outer parts of the disk. These models were used to explain the smaller size and lack of hydrogen in Uranus and Neptune compared with Saturn and Jupiter.

Another focus of the Ames portion of the Center research in 2001 involved a study of dust particles in the optically thin dust layer at the surfaces of these protoplanetary disks. Only a very thin layer of dust particles is directly exposed to radiation from the central star; the rest of the disk is heated by the emission of infrared photons from this dust layer. Because dust absorbs stellar radiation efficiently but radiates only inefficiently in the infrared, this dust layer is typically hotter than the underlying disk photosphere and thus may dominate the emission from the entire system at certain wavelengths. In order to use observations to understand processes occurring in the underlying disk, emission from this dusty surface layer must be accounted for. In addition, these dust particles produce features in the infrared that reveal the mineralogical, chemical and geometric properties of the disk’s grain population, thus providing clues to processes occurring in the disk below.

The theoretical models of the Center have been used to interpret observational data from such NASA facilities as the Infrared Telescope Facility (IRTF), the Infrared Astronomical Observatory (IRAS), the Hubble Space Telescope (HST), and the Infrared Space Observatory (ISO, a European space telescope with NASA collaboration), as well as from numerous ground-based radio and optical telescopes. In addition, they have been used to determine requirements on future missions such as the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the Space Infrared Telescope Facility (SIRTF). ❑

UNDERSTANDING THE CLOUDY SKIES OF BROWN DWARFS

Mark Marley, Andrew Ackerman, and Richard Freedman

Unlike a star, the temperatures and pressures inside a brown dwarf are too small to ever ignite its nuclear furnace. Hence as it ages, a brown dwarfs cools by radiating its primordial energy away to space. During this process a number of important species condense and form clouds within the object's visible atmosphere. First iron, then silicates, and later water form thick clouds. With over 200 brown dwarfs now known, an understanding of these clouds is critical to modeling brown dwarf atmospheres and interpreting their spectra. An innovative collaboration between space and atmospheric scientists at Ames has focused on understanding these unusual clouds in the atmospheres of brown dwarfs. The lessons gained from modeling cloudy brown dwarf atmospheres will also be directly applicable to the first observations of extrasolar giant planets, which are expected to also have cloudy atmospheres.

Whether for a planet's or a brown dwarf's atmosphere, an atmospheric model predicts the variation in temperature and chemical composition with height. Coupled with a description of any clouds this information allows model spectra to be computed and compared with observations. For cloudless atmospheres the modeling procedure is relatively straightforward. Adding clouds to the modeling mix, however, severely complicates the calculation. Previously workers studying brown dwarfs have either ignored the effects of clouds completely or included extraordinarily simplistic clouds that did not behave as do real clouds in the solar system. Both approaches failed to reproduce the characteristics of observed brown dwarfs. Specifically they predict infrared colors for the warmer class of brown dwarfs known as 'L dwarfs' that are either much redder or bluer than is observed. Secondly the simplistic models cannot reproduce the change in color, from red to blue, as the L types evolve to the cooler T type brown dwarfs.

The new cloud model captures some of the most important physics that governs clouds in Earth's atmosphere. Most importantly the model includes the effects of sedimentation of cloud particles, essentially rainfall. Models that include sedimentation produce physically thinner clouds with larger particles than those postulated by other research groups. Unlike complex terrestrial cloud models the new brown dwarf model has only a small number of free parameters, one of the most important of which is a 'sedimentation efficiency factor'. Interestingly efficiency factors of three to five can reproduce some essential aspects of both deep cumulus clouds on Earth and ammonia clouds in the atmosphere of Jupiter.

When used in brown dwarf atmosphere models the new cloud formulation produces much better results than previous efforts. The model not only reproduces the red colors of the L dwarfs and the blue colors of the T dwarfs, it also allows for the first time a consistent explanation for the transition between the two brown dwarf types. As iron and silicate clouds form progressively deeper in cooling brown dwarfs, they sink from sight. The removal of silicate and iron grains then allows water and methane atmospheric absorption to pull brown dwarf colors blueward. Previous models that ignored sedimentation produced clouds that were much too thick; thick clouds prevented the color transition from ever occurring in those cases. Interestingly the same sedimentation efficiency factor that best reproduces some terrestrial and Jovian clouds also best describes ‘rainfall’ in the atmospheres of brown dwarfs. ❑

THE UV PHOTODECOMPOSITION OF MARTIAN CARBONATES

Richard C. Quinn, Aaron P. Zent, and Christopher P. McKay

The effect of UV light on the stability of calcium carbonate in a simulated martian atmosphere was experimentally investigated. Sample cells containing ^{13}C-labeled calcite were irradiated with a Xe arc lamp in 10 millibars of simulated martian atmosphere and a mass spectrometer was used to monitor the headspace gases for the production of $^{13}CO_2$. We have seen no evidence of UV-decomposition of $CaCO_3$ when the calcite sample is exposed to UV light in a simulated martian atmosphere at 10 mbar. Based on the experimental lower limit of detection, the upper limit of photodecomposition on Mars is 3.5×10^{-8} molecules / photon. However, it is most likely that UV photodecomposition of $CaCO_3$ does not occur on Mars due to the high pressure of atmospheric CO_2. In vacuum, the decomposition of $CaCO_3$ may occur due to the photodetachment and photodissociation of CO_3^- radical defects generated by UV light. In a CO_2 atmosphere, the decomposition of $CaCO_3$ is suppressed by the reformation of the UV-generated CO_3^- by adsorbed CO_2 and surface O^- radicals.

In the event that photodecomposition is occurring at rates below 3.5×10^{-8} molecules / photon, the depth to which carbonate is decomposed in the regolith will be limited by the rate at which unreacted material is exposed through wind abrasion and the rate at which mechanical mixing of the regolith can cycle carbonates to the surface. Based on our upper limit of photodecomposition on Mars, the maximum depth of a carbonate-free zone in the regolith would be 10 meters. However, assuming the formation of a carbonate-free zone is limited by the photodecomposition rate and not by the erosion rate, the actual depth of the zone will depend on the rate and depth of mechanical mixing of the soil. If the mixing zone is less than 10 meters deep, the depth of the carbonate-free zone will equal the depth of the mixing zone. If the mixing zone depth exceeds ten meters, the amount of carbonate moved to the surface will exceed the total load of carbonate that can be removed from the surface over geological time, resulting in a nonzero gradient which will move carbonate back into the upper ten meters of the regolith. ❑

REFLECTANCE SPECTRA OF TITAN THOLINS AT CRYOGENIC TEMPERATURES

Ted L. Roush and James B. Dalton

Compositional interpretation of remotely obtained reflectance spectra of outer solar system surfaces is achieved by a variety of methods including matching spectral curves, matching spectral features, quantitative spectral interpretation, and theoretical modeling of spectra. All of these rely upon laboratory measurements typically obtained with the sample at ambient temperatures and pressures. However, surface temperatures of objects in the outer solar system are significantly cooler than ambient laboratory conditions. It has been clearly illustrated that the infrared spectra of silicate materials change as a function of sample temperature, and that these changes can have a significant impact on compositional interpretations.

The optical constants of Titan tholin, a solid residue created by energetic processing of H-, C-, and N-bearing gases, have been used as a coloring agent in compositional models of several outer solar system surfaces. Because these surfaces are well below room temperature we have undertaken a laboratory study to measure the reflectance spectra of Titan tholin with the sample at temperatures of approximately 310, 300, 280, 270, 250, 200, 150, and 100∞K. A subset of these spectra are shown in Figure 12.

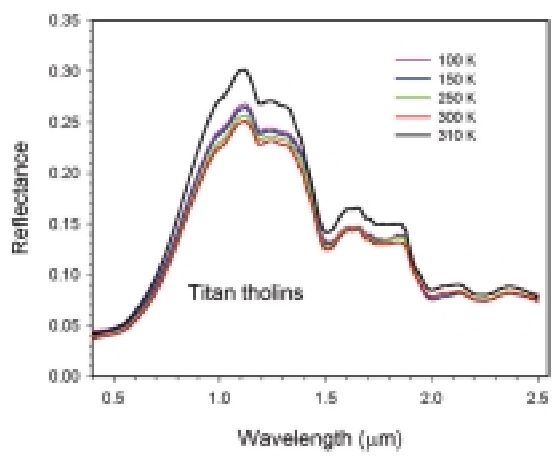

Figure 12: Measured reflectance spectra of Titan tholins at various temperatures.

At low temperature the visual and near-infrared colors of Titan tholin become redder, i.e. the reflectance increases more at longer wavelengths (to ~1.3 mm) than it does at shorter wavelengths, by ~5% as the material cools from 300∞K to 100∞K.

We estimate the effects of temperature on compositional interpretation as follows. The observed ~5% color change is used as a guide to adjust the Titan tholin optical constants reported by Khare et al. The imaginary index of refraction was decreased chiefly in the 0.6-1.3 mm wavelength region corresponding to the most noticable spectral changes in the reflectance data.

Cruikshank et al. used Titan tholin in their models of the surface of the Centaur Pholus. We repeated the calculations of Cruikshank et al. and the results are shown in Figure 13. We then replaced the original Titan tholin optical constants with our values altered to account for temperature effects. The results are also shown in Figure 13. Comparing the results leads us to conclude that, unless there is a sudden change at even lower temperatures, the temperature effects will likely have little influence on the compositional interpretation of the Pholus spectrum.

Acknowledgements: We thank Bishun Khare for supplying the Titan tholin sample and Roger Clark, USGS Denver, for use of the environmental chamber and spectrometer facilities. ❑

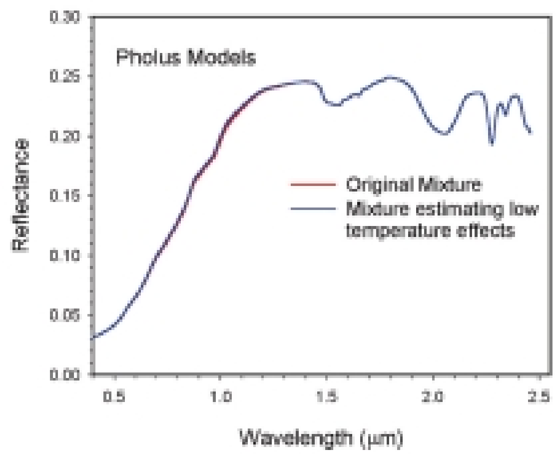

Figure 13: Estimate of the influence of temperature effects on model spectra of Pholus. The red curve is based upon the original model of Cruikshank et al. and the blue curve includes the estimated influence of low temperatures on the optical constants of Titan tholin within the same mixture.

NEW ALGORITHMS FOR MINING TIMESERIES AND IMAGE DATABASES

Jeffrey D. Scargle

A collection of algorithms for extracting structural information from time series and image data has been developed, based on Bayesian segmentation theory. Once the observational errors in the data have been modeled, the procedure is fully automatic, yielding high-level feature information. The software has been tested on synthetic data of known properties, and applied to the analysis of time series data from the Compton Gamma-Ray Observatory's Burst and Transient Source Experiment (BATSE) and two-dimensional positional data from the Palomar Distant Cluster Survey. Application is in progress to spatial power spectrum data on the cosmic background radiation, the solar neutrino flux as a function of time, the detection of planetary transits in various datasets, and other astrophysical problems. Extension to cluster analysis in high- dimensional data sets and other data mining contexts is under way. ❑

GRAIN PROPERTIES OF SOLAR SYSTEM COMETS

Diane Wooden, David Harker, and Charles Woodward

The observation of solar system comets yields insight in the conditions of the primordial solar nebula before the gas and ices were swept up into cometesimals. Mid-infrared observations provide information on the mineralogical content and size distribution of the dust in comets.

Modeling of the thermal properties of dust grains has been successfully performed on several solar system comets including comet Hale-Bopp. Since Hale-Bopp was an extraordinarily bright comet, the Ames Hi-efficiency Faint Object Grating Spectrometer (HIFOGS) obtained spectrophotometric data at mid-infrared wavelengths of 7.5 - 13.5 microns at epochs pre- and post-perihelion. In addition, far-infrared spectra were obtained at 15 - 22 microns post-perihelion. Modeling of the dust grains in Hale-Bopp showed that: 1) the amorphous dust grains became more porous as the comet approached perihelion; 2) the amount of crystalline dust grains increased with a decrease in heliocentric distance; and 3) the dust grains became less porous as the comet receded from perihelion. The latest observations of short-period comet 19P / Borrelly show that the dust grains from this comet are much larger than those from Hale-Bopp.

Learning about the mineralogical content of comets such as Hale-Bopp yields insight into solar nebula processes. For example, the existence of crystalline silicate in comets suggests that amorphous grains (which all but dominate the interstellar medium, out of which the solar nebula formed) have to be processed at temperatures greater than 1000K to form crystalline silicates. Such a processing mechanism implies that either the grains needed to be transported close to the Sun to be heated, crystallized, and then transported out to the comet forming zones where they formed icy mantles before being incorporated into cometary bodies, or some process, such as a nebular shock wave which is the result of gravitational instabilities in the early protoplanetary disk, heated the amorphous silicate grains to a high enough temperature for a sufficient amount of time that the grains were crystallized.

Constraining the properties of dust grains in comets in conjunction with studies of the chemical make-up of solar system bodies leads to a better understanding of the thermal processing, radial transport, and structure of protoplanetary accretion disks.

The NASA Ames HIFOGS continues its mid-infrared spectrophotometric observations of comets including C / 2000 WM1 (LINEAR) in October 2001 and February 2002 at the NASA InfraRed Telescope Facility (IRTF) on Mauna Kea, Hawaii. ❏

STATIC STABILITY OF JUPITER'S ATMOSPHERE

Richard E. Young, Julio A. Magalhães, and Alvin Seiff

One of the particular scientific objectives of the Galileo Probe Mission to Jupiter was to determine the static stability of Jupiter's atmosphere. Static stability is defined as the difference between the vertical gradient of temperature in an atmosphere, called the temperature lapse rate, and the adiabatic lapse rate. The adiabatic lapse rate is the rate of change of temperature with height that would occur if temperature depended on pressure in the same way as it would for an adiabatic compression or expansion of atmospheric gas parcels.

One of the most fundamental properties of a planetary atmosphere is the static stability, which represents the stability of the atmosphere to vertical overturning or mixing. The characteristics of the dynamic meteorology of an atmosphere directly depend on how large or small the static stability is. An atmosphere having zero static stability will exhibit large vertical mixing of air parcels, such that for example, a parcel of air near the surface can easily be carried to high altitudes by winds. On the other hand, if the atmosphere has large static stability, it is quite difficult for an air parcel originally near the surface to be lifted to high altitudes, and therefore that parcel will tend to remain near the surface.

When the Galileo probe, which was managed by Ames, entered Jupiter's atmosphere on December 7, 1995, instruments onboard measured the temperature and pressure of Jupiter's atmosphere as the probe descended. Although this data has previously been analyzed to try to compute the static stability of Jupiter's atmosphere, error sources associated with the pressure sensors, caused by unpredicted thermal excursions in the probe interior, cast serious doubt on the results.

Since the static stability of a planetary atmosphere is such an important quantity affecting the dynamic meteorology of the planet's atmosphere, during this past year a method was developed which avoided completely the errors induced in the probe atmospheric pressure sensors. For a hydrostatic, ideal gas atmosphere, it can be shown that for a probe in equilibrium descent (aerodynamic drag balanced by gravity), the temperature measurements alone can be used to derive the static stability. Unlike the pressure sensors, the Galileo probe atmospheric temperature sensors were unaffected significantly by the thermal excursions which occurred in the probe interior. Thus this method has been applied using only Galileo probe atmospheric temperature data to deriving the jovian atmospheric static stability.

Based on radiative convective models of Jupiter's atmosphere, it was anticipated that the atmosphere was neutrally stable, i.e. had zero static stability. However, observed dynamical features in the atmosphere seemed to imply a small positive static stability. The results from the analysis show that the atmosphere to a depth corresponding to about 20 bars pressure generally is statically stable, exhibiting a static stability of the order of 0.2 K km^{-1}. The stability varies with pressure, such that over limited altitude regions the stability becomes small, but in general the stability is positive.

The implications of a stable jovian atmosphere are significant. The tidal energy dissipation which is associated with orbital evolution of the Galilean moons of Jupiter, and in particular the volcanism on the moon Io, depends on the stability of the jovian atmosphere. The banded structure of Jupiter associated with east-west jet streams requires a stable atmosphere if the winds extend to large depths. Atmospheric wave modes observed to occur at many locations are sensitive functions of the stability. The mode of transport of internal heat flux from the deep interior of Jupiter, ie convective versus radiative heat transport, depends on whether the atmosphere is neutrally stable or statically stable, as does the latitudinal distribution of the heat flux. For all these reasons the derivation of a positive static stability in Jupiter's atmosphere to at least 20 bars pressure is an important finding. ❑

CARBON DIOXIDE CYCLING AND THE CLIMATE OF EARLY EARTH

Kevin Zahnle and Norm Sleep

The continental cycle of silicate weathering and metamorphism dynamically buffers atmospheric CO_2 and climate on geological time scales. In this cycle, silicate rocks and atmospheric carbon dioxide react with the aid of water to form, ultimately, silica and carbonate rocks. The cycle is balanced by the metamorphic branch of the rock cycle, in which carbonate rocks are cooked under pressure to release carbon dioxide gas back into the atmosphere. The carbonate cycle acts as a negative feedback loop that limits climate change on time scales of a hundred million years. Carbon dioxide is an important greenhouse gas. When the climate is warm, carbon dioxide and silicate rocks react more quickly. Meanwhile the continental rock cycle produces metamorphic carbon dioxide gas from old carbonates at a more-or-less constant rate. Thus on net carbon dioxide in the air decreases, and so the climate is cooled. On the other hand, when the climate is cold, the reaction between CO_2 and silicate rocks slows down and CO_2 builds up in the atmosphere and the climate warms. Because the reaction rate between CO_2 and silicates is exponentially sensitive to temperature, the negative feedback is strong, and the climate stays temperate.

Over still longer time scales–billions of years–two other factors become important. The first is the sun evolves. When the Earth was young the sun was only about 70% as luminous as it is today. As the orbit of the Earth is not expected to have changed much since the Earth was fully accreted some 4.4 billion years ago, the early Earth presents a puzzle: geological evidence suggests that Earth has usually been warm enough to have had liquid water oceans, with temperatures and hydrologic cycles not grossly different from those today. Yet the early sun was so faint that, without a significantly stronger greenhouse than today, the Earth should have been encased in ice.

The traditional view has been that the continental weathering cycle described above keeps pace with the evolving sun to keep climate clement. Atmospheric CO_2 levels would have been 100-1000 times higher than today. However, geological evidence, albeit scant, indicates that there was not nearly this much CO_2 during the Archean Eon ca. 2.5-3.8 billion years ago.

The second important difference on billion-year time scales is that the fluxing of carbon dioxide into and out of the mantle becomes important. In the mantle branch of the cycle, CO_2 is outgassed at mid-ocean ridge axes where mantle rocks well up to the surface, while subduction of cold carbonatized oceanic basalt and pelagic sediments returns CO_2 to the mantle. This too is a negative feedback loop, because the amount of basalt carbonatization depends on CO_2 in seawater and therefore on CO_2 in the air. However this feedback cycle does not depend on the climate. The mantle cycle would have kept atmospheric and oceanic CO_2 reservoirs at levels where the climate was cold before ca. 2 billion years ago unless another greenhouse gas was important. At times when life was present on Earth, an attractive candidate greenhouse gas is methane, which the biota produce in vast amounts and which makes a very effective greenhouse gas. But before life arose, Earth was likely to have been on average quite cold.

The earliest Earth, the time before 3.8 billion years ago called the Hadean, is contemporaneous with the heavy impact bombardment of the Moon. Earth was subject to many and frequent impacts by large asteroids and / or comets. Chemical reaction of CO_2 with voluminous impact ejecta and its eventual subduction imply very low levels of atmospheric CO_2 and small crustal carbonate reservoirs in the Hadean. Despite its name, the Hadean climate would have been freezing unless tempered by other greenhouse gases. ❑

THE MARTIAN REGOLITH AND CLIMATE

Aaron P. Zent and Richard C. Quinn

Our objectives in FY01 have been to elucidate the role of the martian regolith in controlling and recording the history of, the martian climate. During FY01, we addressed the question of whether or not water vapor finds a substantial diurnal reservoir in the Martian regolith. Observations disagree on whether or not the atmospheric column abundance of H_2O varies as a function of time of day. Some observations, chiefly from ground-based telescopes, and Russian spacecraft, indicate a tremendous variation over the course of the day. Other observations, specifically those from Pathfinder and the Viking Orbiters, are most easily interpreted to indicate no diurnal variations in H_2O column abundance. Computer models of the atmosphere are unable to predict diurnal variations in atmospheric H_2O abundance. The simplest way to force substantial exchange is to posit that the Martian surface is locally covered with a highly adsorbing clay. These clays have larger adsorptive capacity than ordinary silicates, because they have interlayer sites that are available for adsorption.

In order to force computer models to predict strong diurnal H_2O exchange, the clays must equilibrate with the surrounding pore gases rapidly. However, the equilibration process is temperature dependent, and it is not clear that clays can play a role in exchanging a substantial fraction of the atmospheric column.

To address this issue, we measured adsorption uptake in sodium-rich clay from Wyoming. In Figure 14, we show the results of the uptake experiments. The simplest interpretation of the data is evident in the equilibration time of the two lowest curves. When the soil is held at 211 K, the adsorbed population continues to increase throughout the experimental period, up to 50 hours. In contrast, the case where the soil temperature is held at 273 K, and the R_H is held at 4%, appears to equilibrate over the course of a few hours. Adsorption on martian clays is not a plausible mechanism by which to account for strong diurnal variations in the H_2O column abundance of the martian atmosphere.

Also in FY01, in collaboration with Dr. Robert Haberle, we completed a study of H_2O melting on the martian surface. The times and locations where the surface pressure and surface temperature meet the minimum requirements for this metastability of liquid water were calculated. These requirements are that the pressure and temperature must be above the triple point of water, but below its boiling point. There are five regions on Mars where these requirements are periodically satisfied: in the near equatorial regions of Amazonis, Arabia, and Elysium, and in the Hellas and Argyre impact basins. Whether liquid water ever forms in these regions depends on the availability of ice and heat, and on the evaporation rate. The latter is poorly understood for low pressure CO_2 environments. ❑

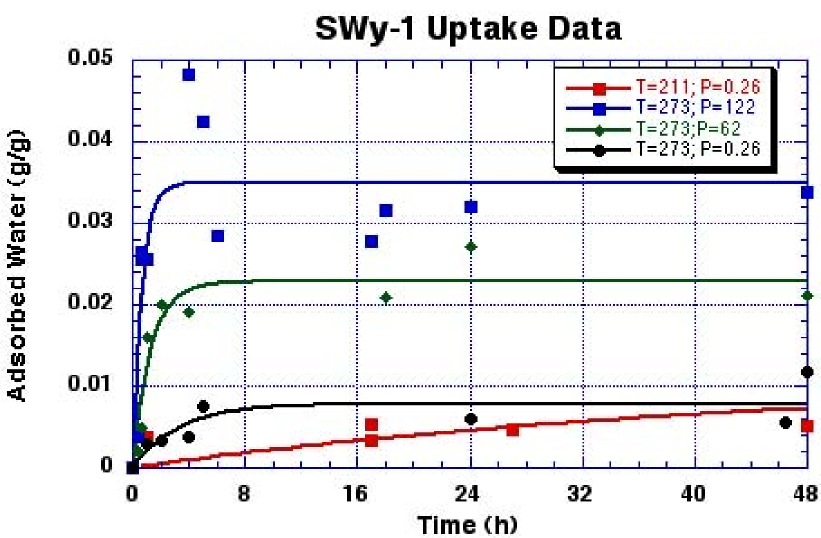

Figure 14: The uptake of water by Mars-analog clays